THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of

M. Chodorow

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ABSTRACT

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

An improved probing system is described, which permits probing of the rf and dc potentials over one face of an amplifying GaAs diode.

Thin specimens (4 mils) allow lower resistivity material to be used and provide excellent isolation characteristics (60 dB cold loss at 1 GHz).

The gain of these devices is found to be limited at high frequency by diffusion and at low frequency by the smallest transverse dimension.

II. GUN OSCILLATION STUDIES

The problem of making cw oscillations in GaAs involves thermal limitations. All cw oscillation to date has been in very thin layers and very small devices in order to keep dissipation down. In this program we are working on the materials and device technology to try and increase the transit length of GaAs devices for cw. Also the use of computer models is leading to new understanding of the space charge behaviors in such devices.

INTRODUCTION

The work under this Grant is generally concerned with communication and information processing in space satellites and more particularly concerned with exploring new devices, particularly solid-state and optical devices, suitable for generation and modulation of electromagnetic waves in the microwave range and upward through the millimeter and optical frequency ranges. Two projects were active under this Grant during the reporting period:

I. Microwave Amplification in High Resistivity GaAs

II. Gunn Oscillator Studies

The Responsible Investigator for this Grant is M. Chodorow.

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

(G. S. Kino and B. Fay)

INTRODUCTION

The objective of this work is to realize a two port unilateral space charge wave amplifier based on the Gunn effect and to check the theory of wave propagation in finite semiconductors.

The active medium consists of a GaAs diode biased between the negative differential conductance threshold and the threshold for current oscillations, the latter being a function of the diode $n\ell$ product as well as of its thickness and dielectric environment.

PRESENT STATUS

A. Experiment

A new probing system was put to use, allowing us to sample the rf or dc potentials over one face of a sample operating as an amplifier. The sample configuration is identical to that described in the previous report.

The probe itself is a short section of semi-rigid miniature coax whose center conductor is etched down to a 1 mil point. This point is dragged over the probed face with the aid of a micromanipulator and can be observed at will through a microscope. It was found necessary to prevent direct contact between the probe and the semiconductor by interposing a thin sheet of mylar in order to obtain reproducible results.

A schematic of the probe circuit is shown in Fig. 1. The same probe can be used for measuring the dc potential, with a different receiving circuit.

Figure 2 is a typical rf potential profile in the longitudinal direction. The modulation is caused by interference between the slow space charge wave and a leakage electromagnetic wave; thus the modulation period corresponds to the space charge wavelength in the sample at that particular frequency. The phase velocity of 1.6×10^7 cm/sec deduced from Fig. 2 is in excellent agreement with the electron drift velocity predicted from the Ruch-Kino velocity-field characteristic assuming a uniform dc field across the diode.

Measurement of the transverse variation of the rf potential revealed a tendency for the signal to peak in the center, particularly near the anode, as shown in Fig. 3.

We have performed some amplifier tests on thin diodes (typically 4 mils thick, 32 mils long) made of lower resistivity material (300 ohm-cm) which can be tuned to provide 10-20 dB of terminal gain and a maximum output power of a few milliwatts around 1 GHz (see Fig. 4). The dc resistance of such a diode is typically 35 K ohms with a "cold" rf transmission loss of over 60 dB.

B. Theory

The inclusion of carrier diffusion in the current equation leads to a high frequency falloff of the growth rate, in the one-dimensional theory. The dispersion relation obtained for this case:

$$\beta^2 - j \beta \beta_D + \beta_D (j \beta_e + \beta_C) = 0 \quad ,$$

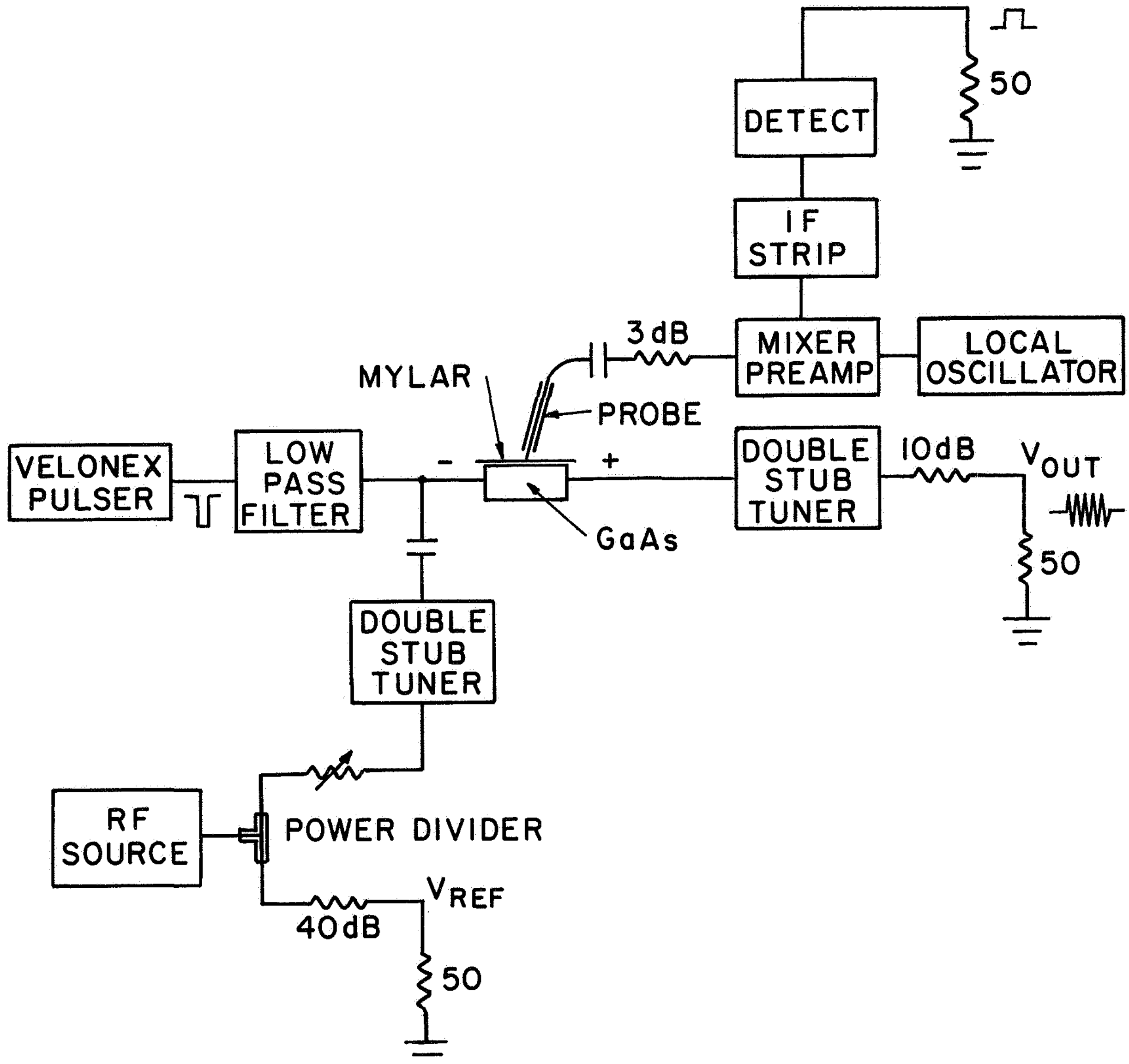


FIG. 1--RF probing circuit.

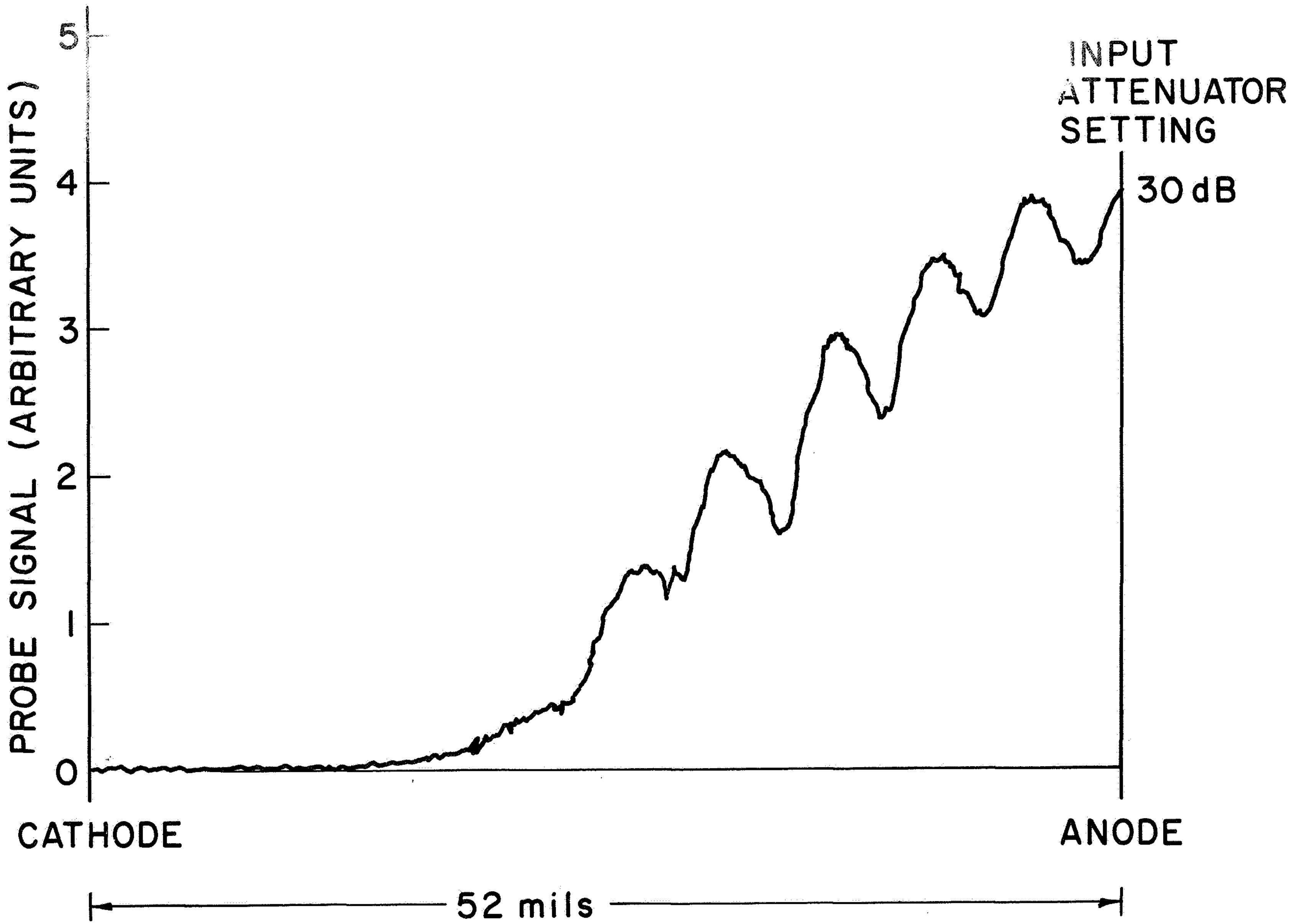


FIG. 2--RF potential profile at f = 1265 MHz.

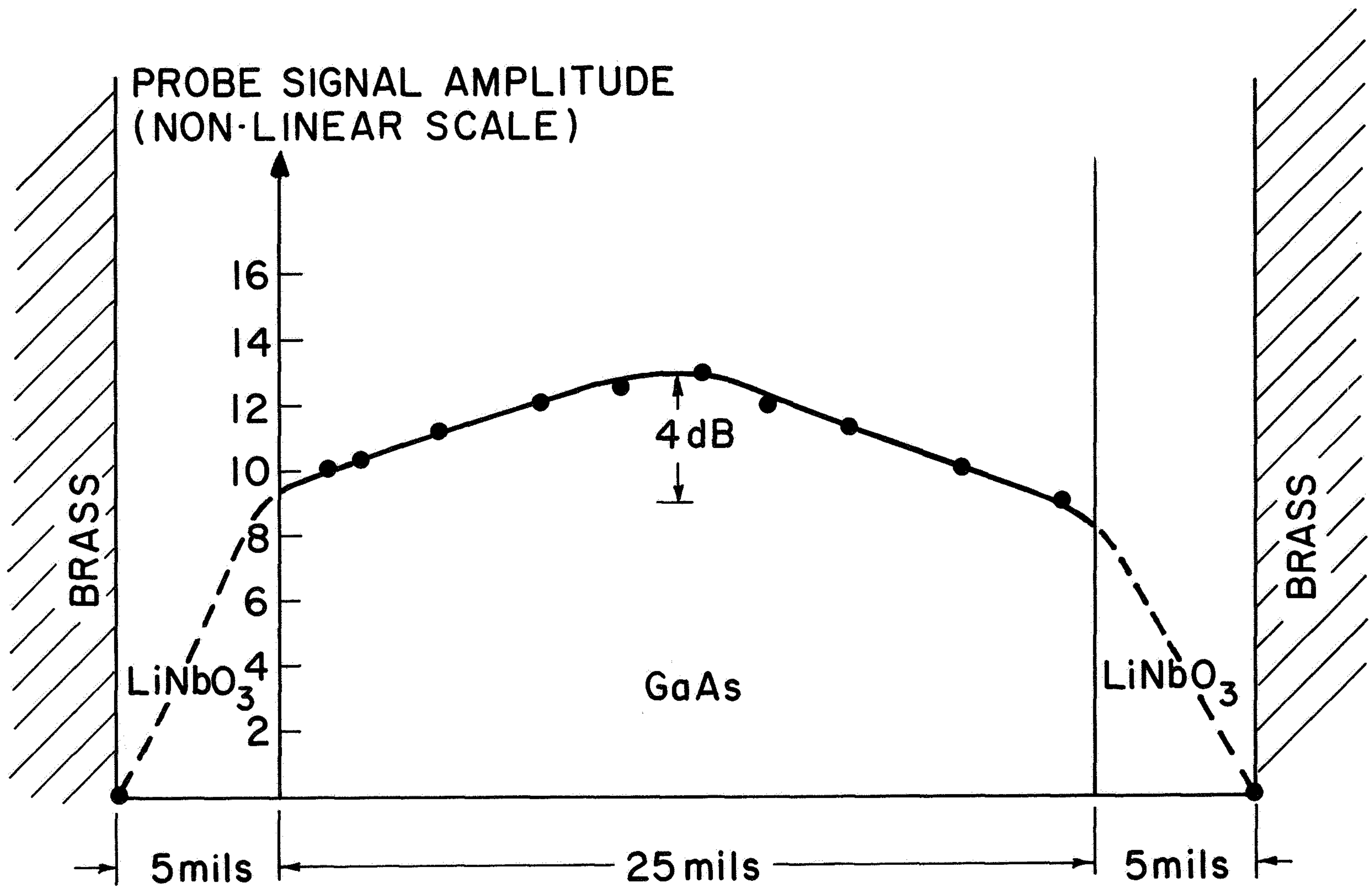


FIG. 3--Transverse variation of rf potential near the anode (f = 520 MHz).

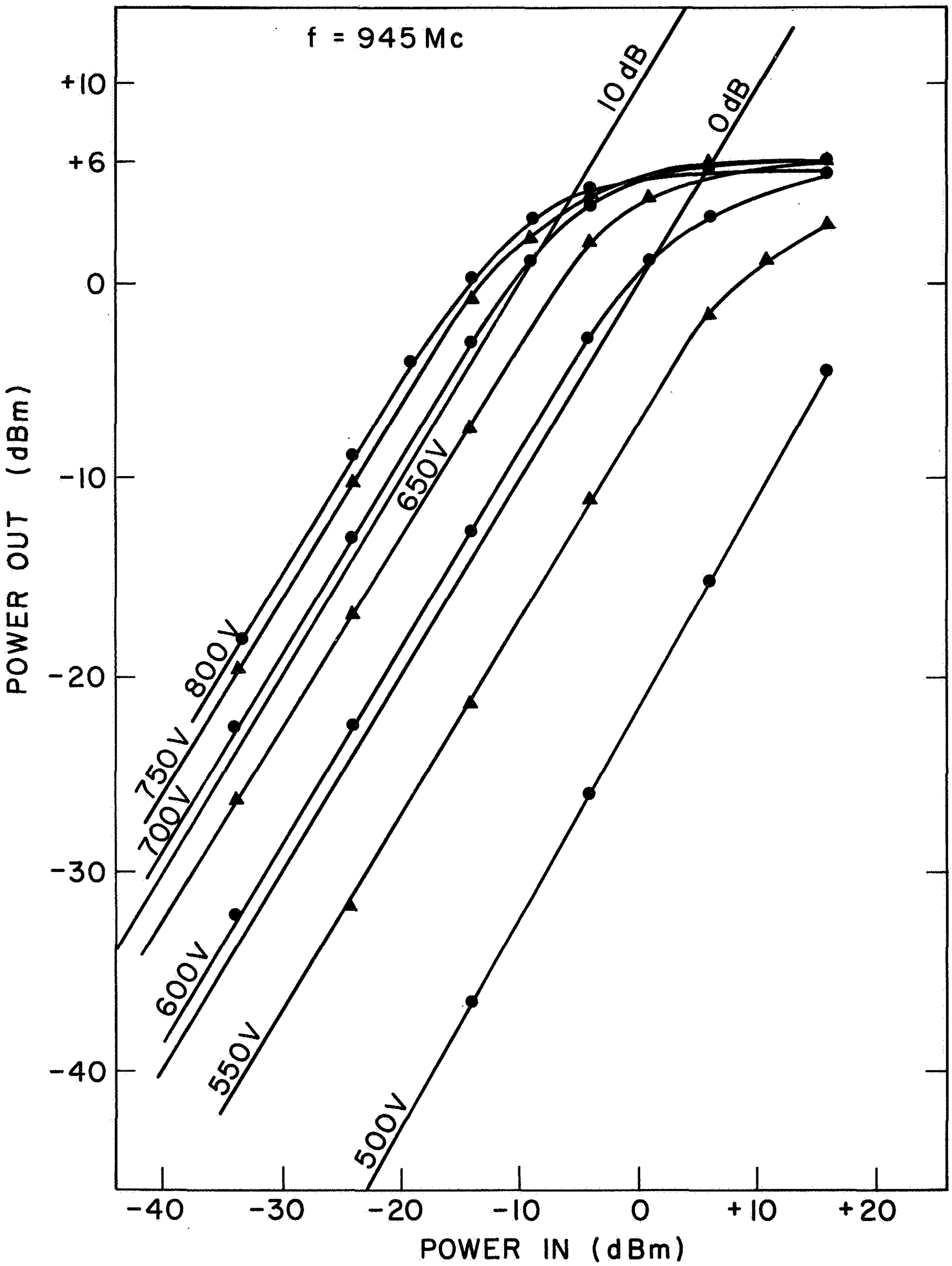


FIG. 4--Output power is input power.

where

$$\beta_D = \omega_D/v_0, \; \beta_c = \omega_c/v_0 \;, \; \beta_e = \omega/v_0$$

$$v_0 = \text{electron drift velocity}$$

$$\omega_D = v_0^2/D = \text{diffusion frequency}$$

$$\omega_C = \frac{en_0\mu}{\epsilon} = \text{dielectric relaxation frequency}$$

can be solved exactly and the imaginary part of the propagation constant β is seen to decrease monotonically with frequency, reversing its sign at a frequency corresponding to $\beta_e^2 = \beta_C \beta_D$. Hence there exists an upper frequency cutoff dictated by the semiconductor resistivity. The calculated cutoff frequencies are 2 GHz for 1000 ohm-cm material and 6 GHz for 100 ohm-cm material.

On the low frequency end, we also expect a falloff of growth rate due to finite transverse dimension and to the presence of grounded metal electrodes. There exists, therefore, a frequency for maximum gain for each device, although the resonance can be made fairly broad by proper choice of material resistivity and sample dimensions.

In order to gain some insight into the saturation mechanism, we have recently started a computer study of large rf signal effects.

In the coming months, we plan to continue our probe studies on relatively wide samples in order to check the results of the two-dimensional theory we are presently extending. We also intend to convert the present amplifier system to a strip line configuration which should prove more suitable for specimens of small thicknesses.

II. GUNN OSCILLATOR STUDIES

(C. F. Quate and J. A. Higgins)

INTRODUCTION

As in previous reports the contents of this report indicate achieved progress on the three lines of endeavor which come under the above heading. These are:

(a) Growth of high purity GaAs

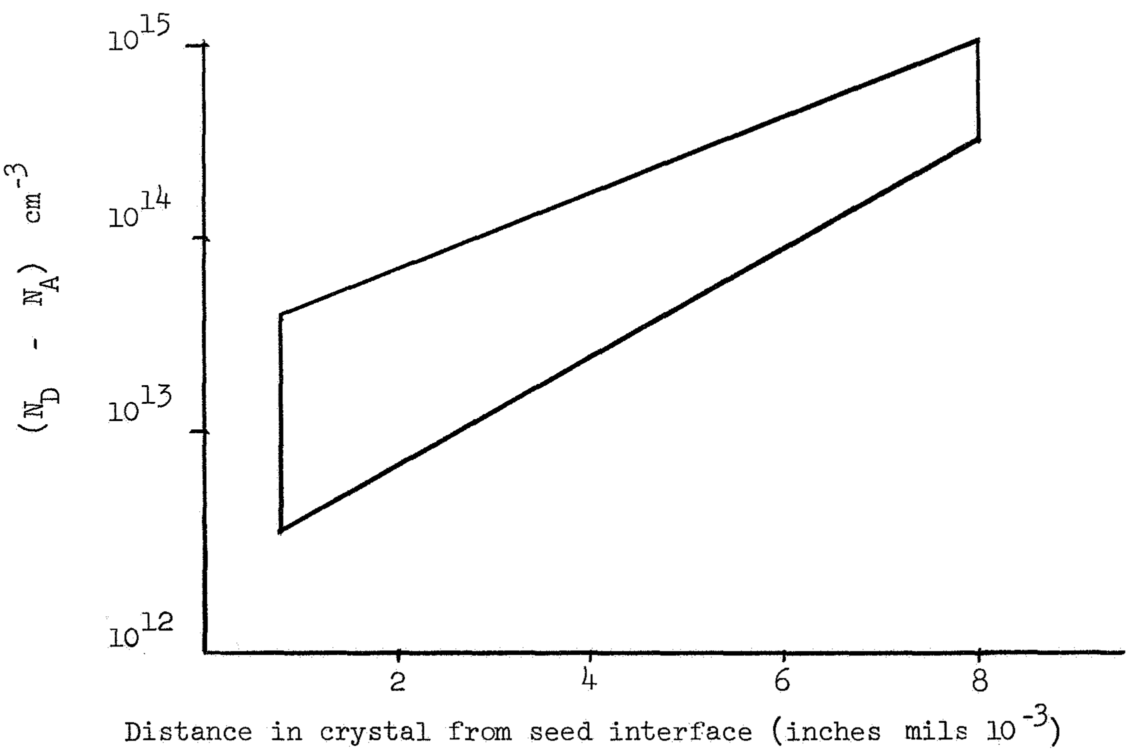
(b) Fabrication of long CW oscillators

(c) Computer studies of GaAs devices.

PRESENT STATUS

A. <u>GaAs Crystals</u>

A more complete investigation of the crystals grown in the tipping system has revealed inhomogeneity problems. The main effect uncovered by these investigations is a variation of doping or net impurity level in the direction of growth of crystals. This is generally in the ⟨111⟩B direction. This carrier concentration variation is depicted in Fig. 1.



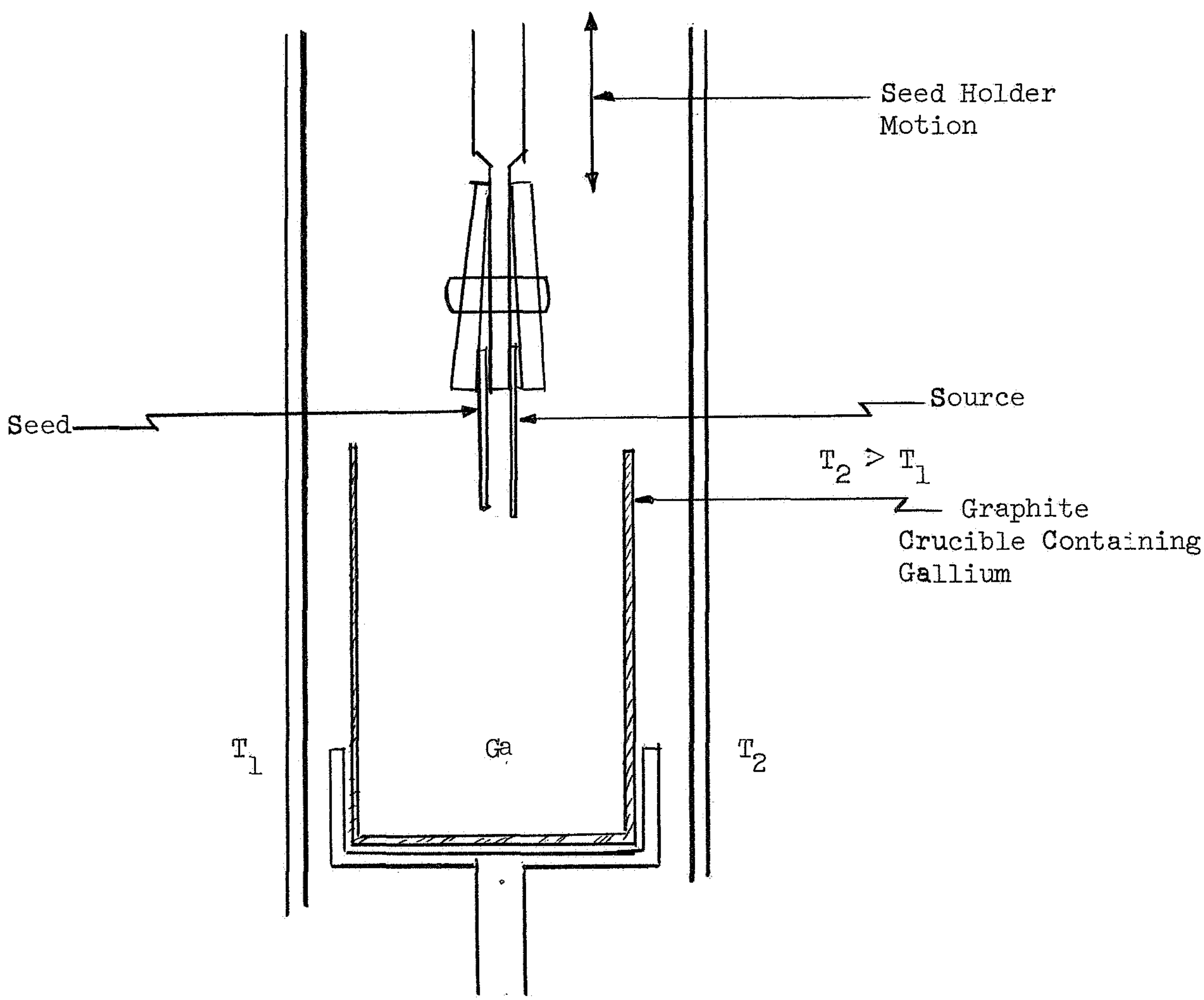
As can be seen from the above figure, the resultant resistivity of the material varies over a range 1 - 100 ohm-cm. At present this is thought to be due to a variation of the effective distribution coefficient of the impurity (believed to be oxygen) as an acceptor making the high resistivity portion of the growth highly compensated material. This conclusion is based on measurements of mobility at low temperatures ($77^{\circ}K$).

The high resistivity material has the following characteristics: (a) It is highly photosensitive and measurements of the photocurrent with monochromatic light reveal the presence of acceptor levels which are relatively shallow. (b) The mobility, even when measured at low temperatures, may be quite low unless the free carrier population is increased by radiation of light onto the surface. In the dark, anomolous nonreciprocities, which are not properties of the ohmic contacts, make themselves apparent in samples greater than 1 mm square indicating inhomogeneities in the material laterally.

The lower resistivity portions of the grown crystal lack the photosensitivity mentioned above, but have high mobilities with liquid nitrogen mobilities that are as high as can be expected for the resulting net carrier concentration revealing that compensation is low here.

For the reasons above, most crystal growth of late has been done at lower temperatures where the growth rate is slow and compensation at a minimum. It is hoped that techniques have been evolved which give low compensation. We have succeeded in bringing down the net carrier concentration for lower temperature growth by paying special attention to both the gallium and the GaAs used for source material. It has been consistently shown that unprepared gallium will increase the net carrier concentration quite considerably above the net carrier concentration obtained from gallium suitably "cured". Also, inhomogeneity is considerably improved. However, the major source of impurity is the GaAs source material. Use of pregrown source (i.e., "second generation") has brought about a tenfold improvement in net carrier concentration. Mobilities have not yet been measured.

We have endeavored to learn from the inhomogeneities in these crystals how to make better crystals in thin films. The lessons learned are being embodied in a new vertical system which is illustrated in principle in Fig. 2.



This system is being constructed and will go into operation soon. The principal advantages shall be (1) a growth at a constant temperature, (2) a controlled speed of growth, (3) a large "sink for impurities" in that the system will use 30 gm of gallium, and (4) it will enable us to terminate growth quickly to obtain thin layers.

B. Device Fabrication

A new liquid epitaxial system using a solution of GaAs in tin has been constructed for the purpose of growing thin layers of degenerate GaAs on liquid epitaxial material. This is the outcome of much effort and failure to make adequate contacts to higher resistivity GaAs using the metallurgical systems contacts. The metal semiconductor contacts fail on liquid epitaxial material because the GaAs tends to be depleted at a surface, particularly if it has been heat treated. Then the germanium, usually used to make the dopant which diffuses into the GaAs from the molten phase during alloying, prefers to act as an acceptor. The result is a nonlinear or high resistance contact. In vapor phase material or material grown from the melt, the inherent impurities in the GaAs prevent the acceptor-like behavior of the germanium. An alternative, although less favored, argument assumes nonstoichiometry and states that the germanium finds many more arsenic vacancies than gallium vacancies in the liquid epitaxial material.

In making good contact to gallium solution grown GaAs, it is necessary to etch the surface and immediately regrow thereon a degenerate layer. This has been done successfully on our new system.

At the present moment it is more useful to use the system to inspect different growth rates for different faces of a polar crystal such as GaAs. Tricky problems arise in making thin layers simultaneously on the $\langle 111 \rangle$A and $\langle 111 \rangle$B faces due to the fact that growth rates are so different on each face.

Silicon dioxide masking may be used in the above system for defining areas of contacting. Techniques for making long surface oriented devices are now being perfected.

C. Computer Studies of GaAs Devices

We had shown in the last report how the small signal behavior of a short diode differed markedly from the usual large signal behavior.

Attention on the computer has been devoted to developing programs which show the role played by the harmonics in increasing efficiency, extending bandwidth and facilitating the switchover into a large signal mode of operation for GaAs devices in circuits. Control of the space charge in a diode is a function of the impressed voltage and so wave-shaping as accomplished by the presence of harmonic voltages can spell the difference between oscillatory power at a circuit-controlled frequency and high efficiency; and little or no power. This, then, is a matter of finding the optimum size and phasing of the harmonic components.

We have devised a program which will be used to work on the starting problem and show the important role assumed to be played by transit time frequency and subtransit frequencies in switching over to the circuit-controlled oscillation.

Some time has been spent endeavoring to arrive at a feeling for the part played by device size (i.e., length ℓ) in determing whether accumulation or dipole modes are most stable. No definite outcome is available here yet.

We have confirmed both Wessel-Berg's results and the measured form of E field distribution in GaAs devices whose $n_o \ell$ products are below 2×10^{11} using modified versions of this program. Modifications involve changing the velocity field curve in the latter case although this change was not very significant, as this time we simply used a piece-wise approximation very similar to the experimentally measured values for velocity and diffusion vs electric field.